

November 1981

Excess Noise in Tunable Diode Lasers

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SUMMARY

A method for identifying excess noise in tunable diode lasers (TDL's) is presented as well as results from several evaluations of TDL's. It is shown that excess noise is not invariably associated with a particular wavelength, and that it is often possible to select injection current and temperature settings which yield performance approaching ideal (i.e., no fluctuations of output energy). Consequently, the existence of excess noise does not necessarily eliminate an individual TDL from application as a local oscillator if fine control of temperature and injection current is used.

INTRODUCTION

The application of laser heterodyne spectroscopy to measure stratospheric trace constituents from spacecraft observational platforms has been previously discussed (ref. 1), and sensitivity analyses of a Laser Heterodyne Spectrometer (LHS) instrument have been performed to assess the feasibility of detecting minor species (i.e., C_2O , O_3 , and H_2O_2) in the stratosphere from space (ref. 2). The advantages of laser heterodyne techniques in providing high spectral resolution of less than or equal to 0.001 cm^{-1} and simultaneously high signal-to-noise ratio are important for measuring those stratospheric species for which it is necessary to achieve a Noise Equivalent Width (NEW) of less than or equal to 10^{-6} (ref. 3). Tunable diode lasers of the Pb-salt type have been used to obtain ground-based solar absorption spectra of CO_2 , H_2O , O_3 , and HNO_3 (ref. 4), with a spectral resolution of 0.007 cm^{-1} . A current limitation in using TDL's as local oscillators is the presence of extraneous, or "excess," noise above shot-noise limited performance. The presence of excess-noise effects at radio frequencies (RF's) (20 MHz to 1.2 GHz) have been previously reported for III-V (GaAs) semiconductor lasers (ref. 5). The existence of excess noise can severely reduce the available signal-to-noise ratio in heterodyne receivers and, consequently, the actual NEW can be reduced to values well below other high-resolution sensor systems.

In this paper, measurements from laboratory experiments are presented which have yielded techniques by which the presence of excess noise can be readily identified at various operating points for semiconductor lasers. These measurements can be readily implemented as a "screening test" prior to delivery of TDL's for use as local oscillators in stratospheric application experiments. Furthermore, it is shown that regions of minimum excess noise can be set by control of the laser operating temperature and injection current. Results are presented which suggest that excess noise exists in diode lasers regardless of the technologies used for their fabrication. It is also shown that excess-noise effects are not uniquely associated with a particular wavelength of laser radiation, so that the simple existence of excess noise need not eliminate any particular laser from a particular application at a well-defined wavelength. Finally, evidence is given to demonstrate the validity of the excess-noise identification techniques in a direct measurement of atmospheric H_2O from a ground-based measurement, in which it is shown that excess noise can be adjusted to reduce excess-noise contamination of an atmospheric absorption feature.

DISCUSSION OF HETERODYNING

Optical heterodyning is a well-established technique (ref. 6) and is not the primary subject of this paper. However, since excess noise can have such a severe effect on realizable system signal-to-noise ratio, it is important to review the general principles involved in optical heterodyning. Shown in figure 1 are the basic components of an optical heterodyne system. A source of coherent radiation (known as the local oscillator) is directed onto a photomixer (generally a high-speed photodiode). The source of signal radiation is also directed to the photomixer. The two radiant powers are combined at a beam splitter, and the added signals are detected by the photomixer. The effect of the detection process is to frequency mix the local oscillator against the signal source to generate a difference frequency at the output of the photomixer. Difference frequencies between the signal source and the local oscillator which lie within the frequency response of the photomixer are detected. In addition, the photomixer produces a dark leakage current and a photocurrent proportional to the sum of the received average signal power and the local oscillator power. In normal operation, the local oscillator power strongly dominates the signal power, and the photocurrent itself is generally much greater than the photomixer leakage current. The output of the photomixer is amplified and sent to signal-analysis electronics, which can be either a synchronous detector or a radio frequency power meter.

DEPARTURES FROM IDEAL-NOISE CHARACTERISTICS

Early work in evaluating diode lasers in communications systems identified that there were high-frequency amplitude perturbations in the output of the diode laser which appeared in the associated amplifiers as RF noise, and measurements were made to quantify the phenomena (ref. 7). Reference 7 deals with III-V materials (GaAs) and not II-VI (Pb salt), but theoretical analyses have indicated that RF noise is an inherent characteristic of lasers regardless of material (ref. 5). Consequently, it must be assumed that a similar phenomenon appears in Pb-salt tunable diode lasers. Published data on heterodyne signal-to-noise ratio for TDL's have also indicated that under certain conditions, TDL's show degradation in signal-to-noise ratio compared with CO₂ laser local oscillators which have achieved performance approaching ideal coherent sources (ref. 8).

There are, in the ideal case, basically five signals at the output of the pre-amplifier: (1) the shot noise from the local oscillator (LO); (2) the signal-induced photocurrent; (3) a beat signal between the LO and the signal; (4) the noise from the preamplifier; and (5) the quantum self noise in the signal. The optimum signal-to-noise ratio is generated from the detected beat signal and the fluctuations arising from the two inherent noise sources, LO shot noise and preamplifier noise.

The relation between direct current (dc) in a photodiode I_{dc} and the induced shot noise i^2 can be written as

$$i^2 = 2qI_{dc}$$

where q is the electron charge. When using a preamplifier of real-input impedance R_i , internal-noise power $(F - 1)kT_o$, and power gain G_p , there is a total output-noise power in unit bandwidth P_o of:

$$P_o = G_p [2qI_{dc}R_i + (F - 1)kT_o] \quad (2)$$

where F is the noise factor of the preamplifier, k is Boltzmann's constant, and T_o is the output temperature.

A plot of output power versus total photodetector current would ideally be a straight line with a zero photocurrent intercept proportional to the amplifier noise. Excess noise in the RF bandpass would be manifested as a departure from the straight line. (See fig. 2.)

APPARATUS

To identify the departures from ideal performance caused by TDL excess noise, a system for monitoring the noise was assembled similar to the one in figure 1. A block diagram of this system is shown in figure 3. Besides the local oscillator, photomixer, and preamplifier, a 3- to 115-MHz bandpass amplifier was included in the system. The bandpass amplifier output was passed to a square-law RF detector. Also a separate output was provided from the amplifier for measurements of the dc output of the photomixer.

EXPERIMENTAL RESULTS

Several Pb-salt TDL's representing the current major fabrication technologies were tested. Each TDL was characterized by monitoring both total RF power in the bandpass of the final amplifier and the photoinduced direct current in the photomixer, as the TDL drive current was driven by a linear ramp generator over the entire operating-current limits. Representative results are summarized in the oscilloscope traces of figure 4, in which the total RF noise is the top trace and the bottom trace represents the photoinduced current in the photomixer. In some cases, the excess noise is so large that the "quiet regions" appear almost noiseless. Nevertheless, close inspection shows that in the quiet regions there is a slight upward change in the noise level consistent with equation (2). It was also observed that even in the quiet regions, the noise would approach, but not equal, the true shot-noise values. The residual limits were subsequently found to vary from laser to laser and among the quiet regions. The regions of excess noise could, depending on the TDL, represent a small fraction to almost all of the total operating range of the TDL. It was also found that the excess-noise regions were a function of TDL operating temperature.

Since the application of TDL's to heterodyne spectroscopy would require quiet operation at specific wavelength intervals, tests were conducted to determine whether or not excess noise is uniquely associated with a particular wavelength. To perform this evaluation, an ammonia gas cell was placed in the path of the TDL radiation to simultaneously observe both excess noise and the absorption line. The absorption line is clearly visible in the bottom traces of the two oscilloscope traces of figure 5. As shown in figure 5(a), excess noise was being generated close to the peak of the ammonia absorption lines for the operating temperature of the TDL. The operating temperature was changed and the TDL injection current adjusted to maintain the wavelength approximately constant. As shown in figure 5(b), the excess noise was reduced so that only a slight contamination of the absorption remained. This and similar tests on other lasers demonstrated that excess-noise regions are not uniquely associated with a particular wavelength. It should be emphasized that the excess noise has not been eliminated, nor would this procedure ensure that every contaminated wavelength region could be made free of excess noise. What is important is that this method of detecting excess noise and attempting to influence the excess

noise makes it possible to completely determine the acceptability of a TDL for use at a particular wavelength with respect to the existence of excess noise.

As a demonstration of the foregoing results in an atmospheric heterodyne application, the laboratory system was modified to permit the Sun to be used as a signal source, and the photocurrent output was replaced by the detected heterodyne signal output. Shown in figures 6(a) and (b) are water vapor absorption lines near 909 cm^{-1} with the bottom traces representing the total RF noise. In figure 6(a), there is a significant drop in the excess noise partway through the trace. The absorption line is shown to contain a feature inconsistent with the known spectroscopy of this absorption line in the Earth's atmosphere. The operating point for this laser was changed and the result was the cleaner RF noise scan in figure 6(b), with the uncontaminated atmospheric absorption line shown.

CONCLUDING REMARKS

A simple method for identifying the regions of excess radio frequency (RF) amplitude noise in tunable diode lasers (TDL's) has been presented. Tunable diode lasers fabricated with the currently available technologies have been tested and found to possess excess noise which varies from device to device and with changes in operating point. It has been shown that excess noise is not necessarily associated with a particular wavelength and that minimizing excess noise can sometimes be effected through changes in operating conditions. An important point to be made is the ease with which excess-noise regions can be identified. In an automated application, a computer could easily compare the predicted RF-noise power with the amount actually generated and could select quiet regions for operation. In conjunction with a wavelength identification system, a computer system under complete automation could in principle select operating conditions in temperature and injection current which minimize excess-noise effects at wavelengths overlapping absorption lines of atmospheric molecules. Considerable savings in selection cost for TDL's for a particular application can result from this procedure.

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September 17, 1981

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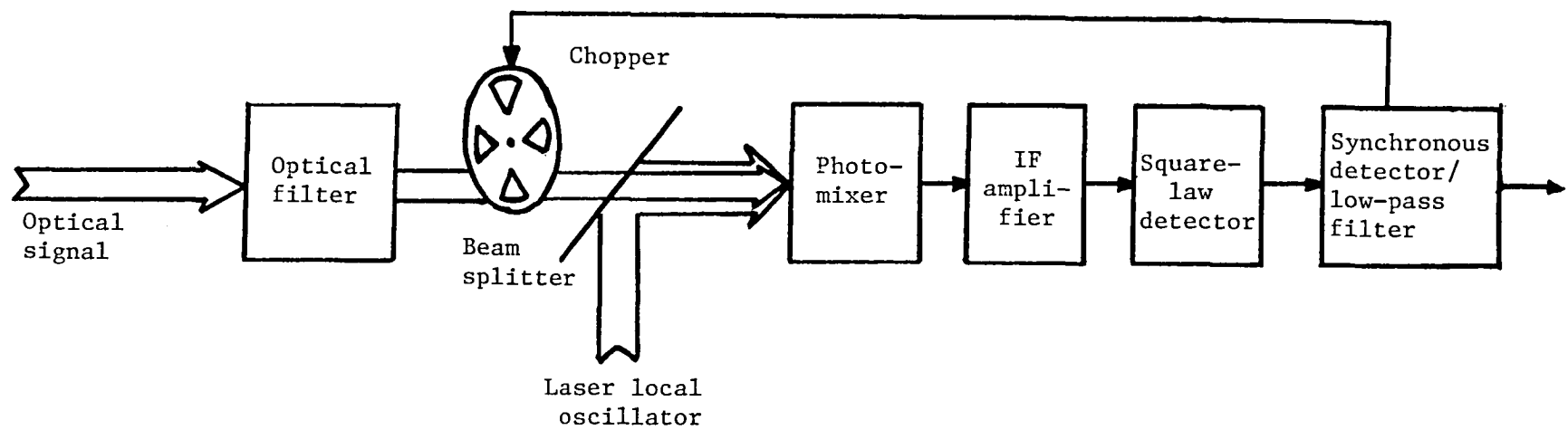


Figure 1.- Schematic of an optical heterodyne receiver.

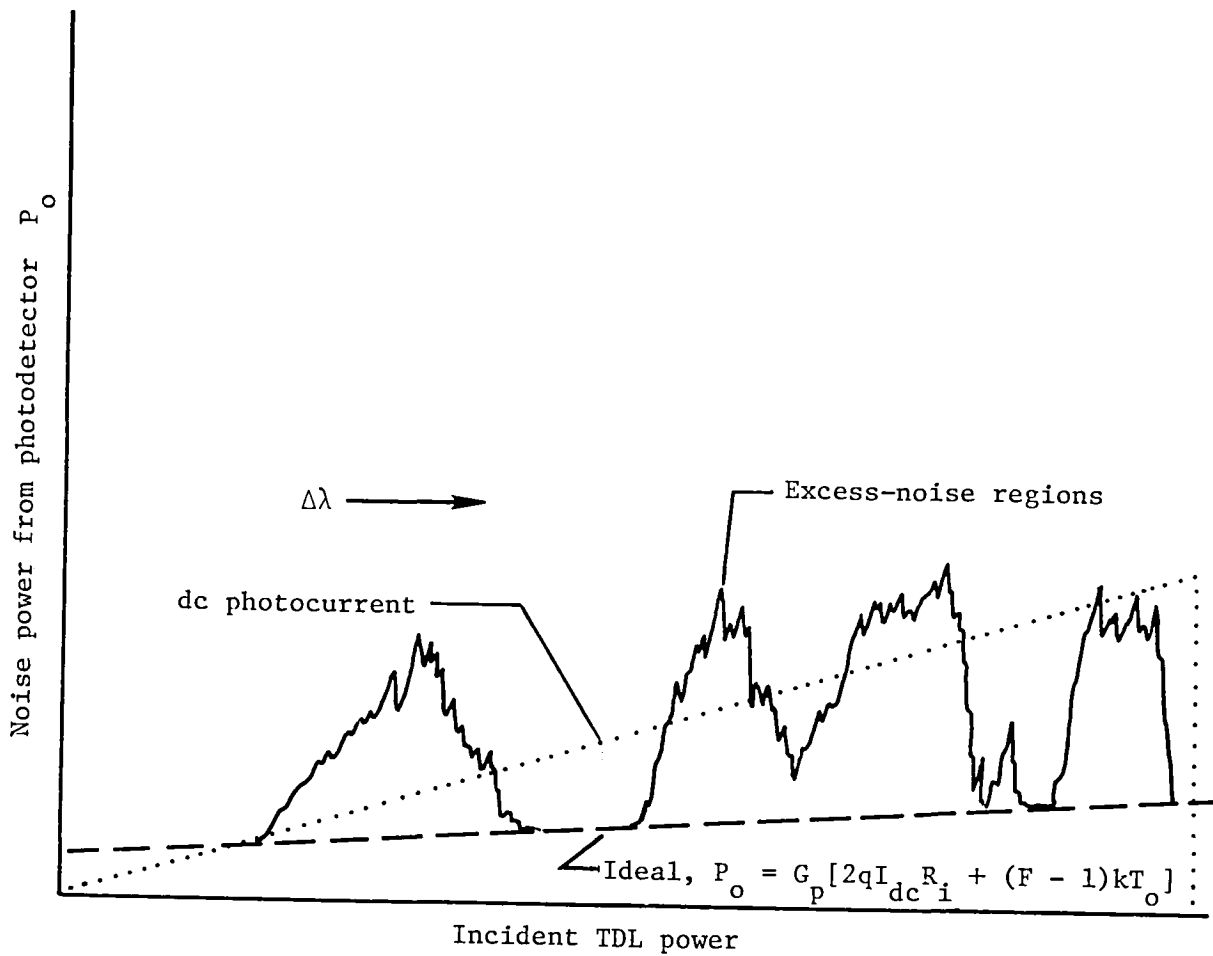


Figure 2.- Incident TDL energy on photodetector plotted against noise power from photodetector. ($\Delta\lambda$ indicates changing wavelength.)

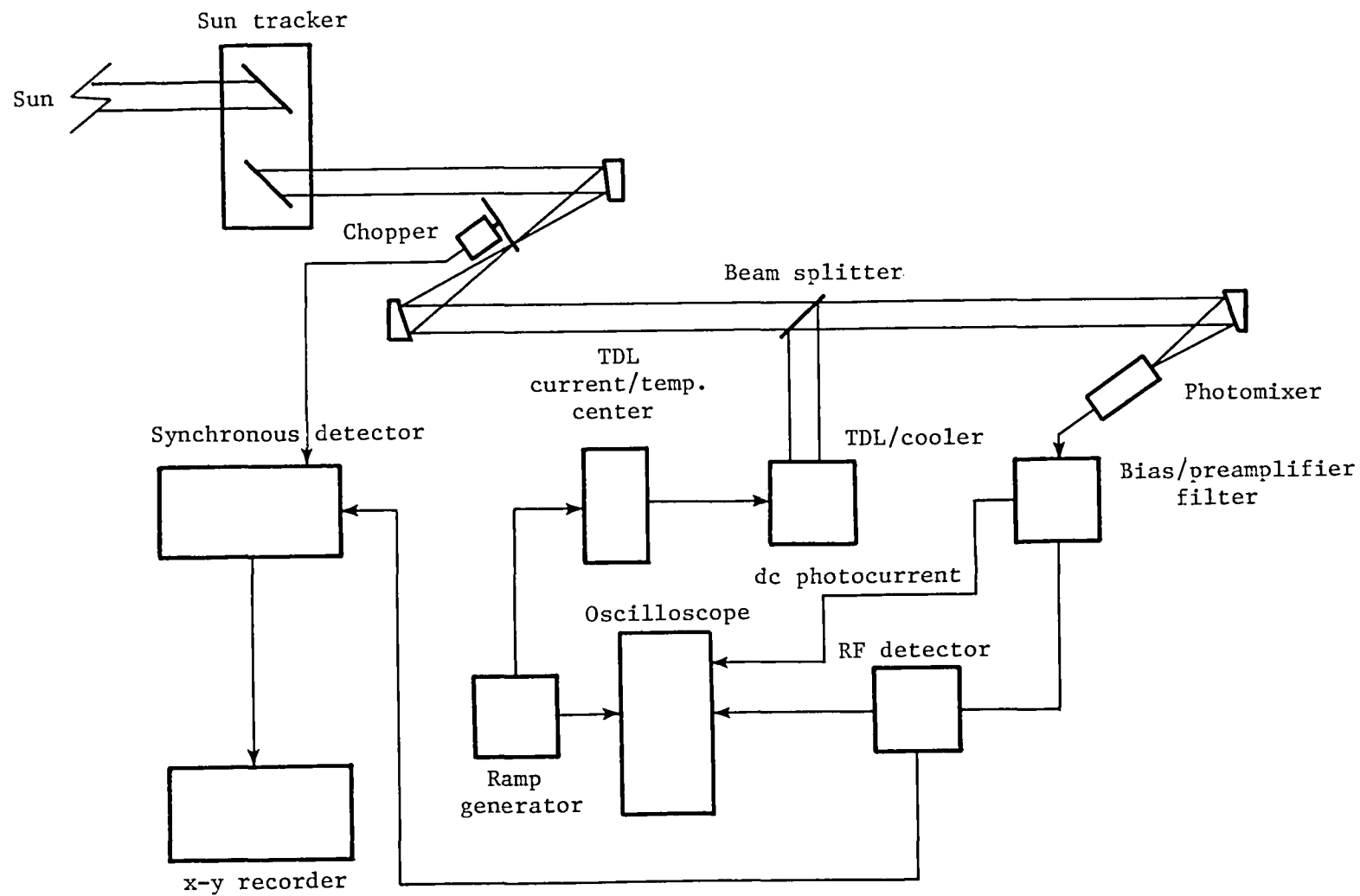
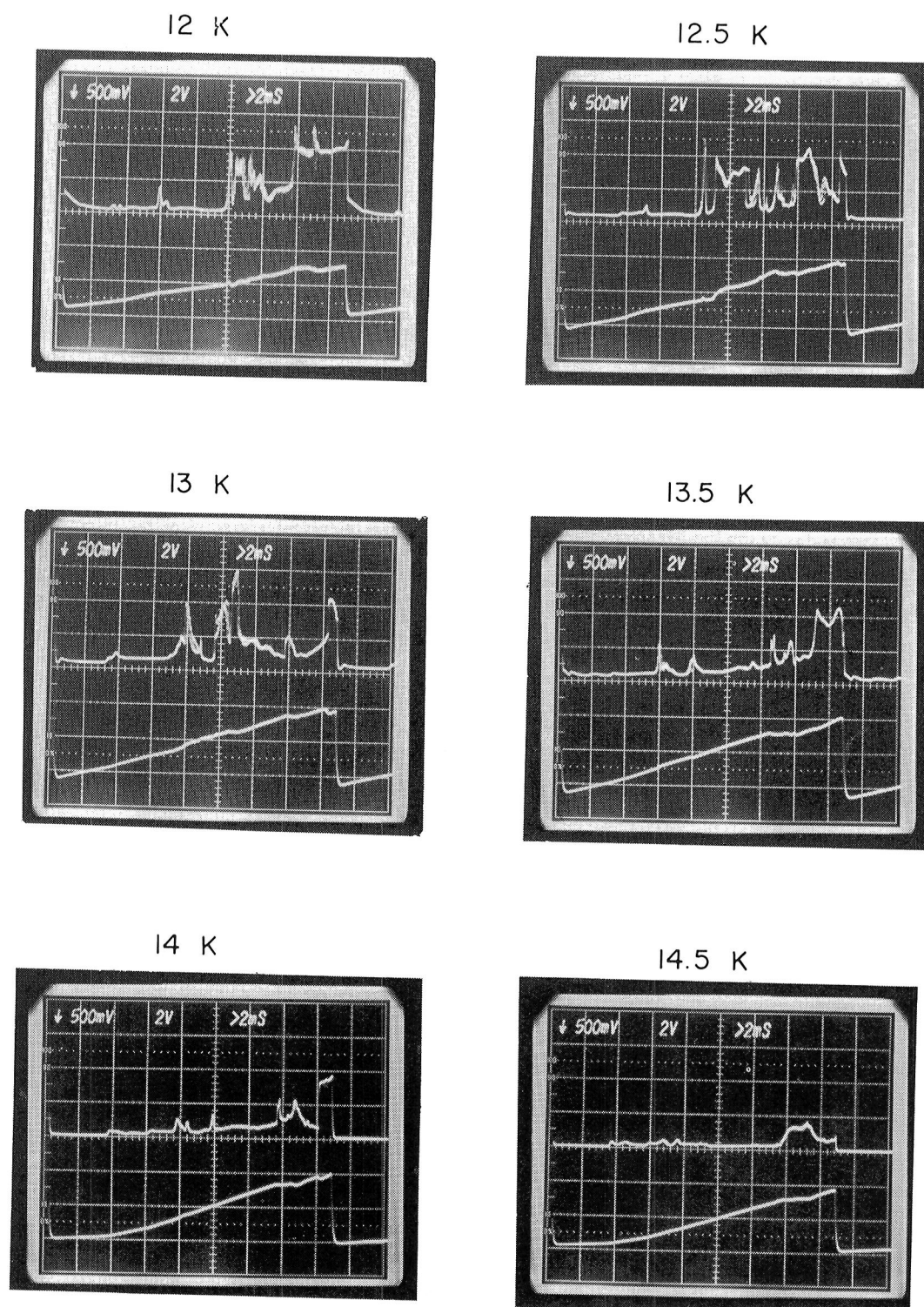


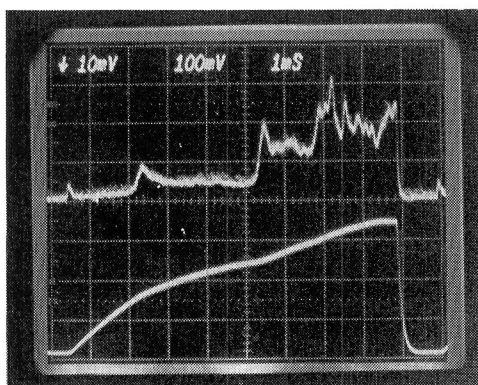
Figure 3.- Heterodyne and excess-noise-measurement system.



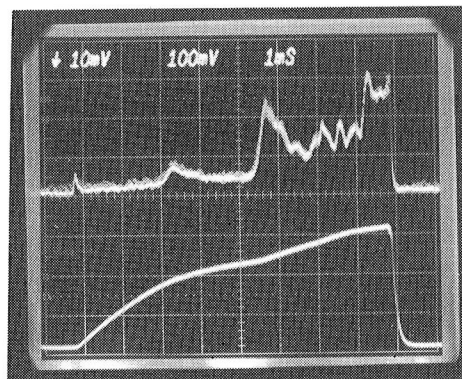
(a) First TDL.

Figure 4.- Oscilloscope traces from two different TDL's showing effects of different operating points on excess noise.

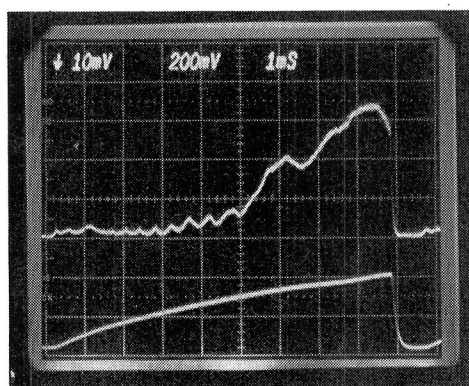
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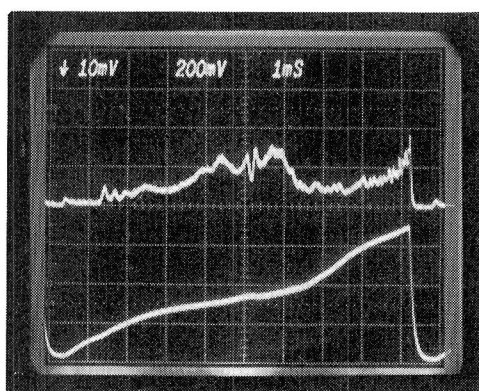
12 K



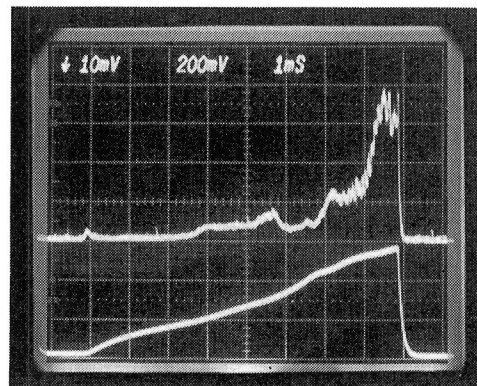
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13.5 K

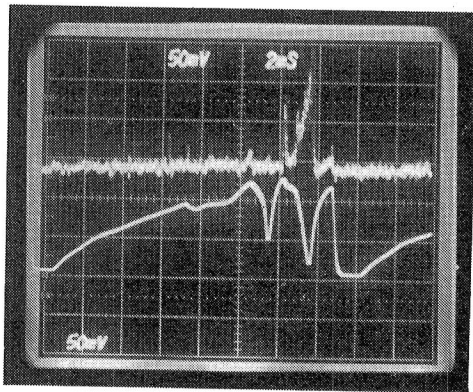


14 K

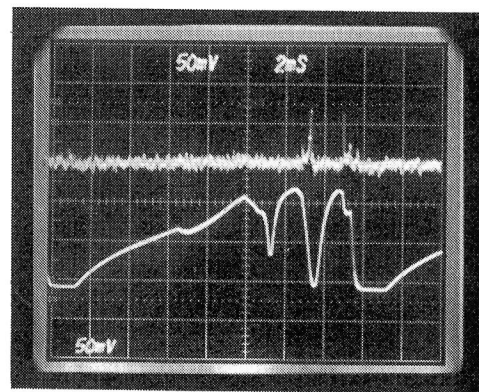


(b) Second TDL.

Figure 4.- Concluded.

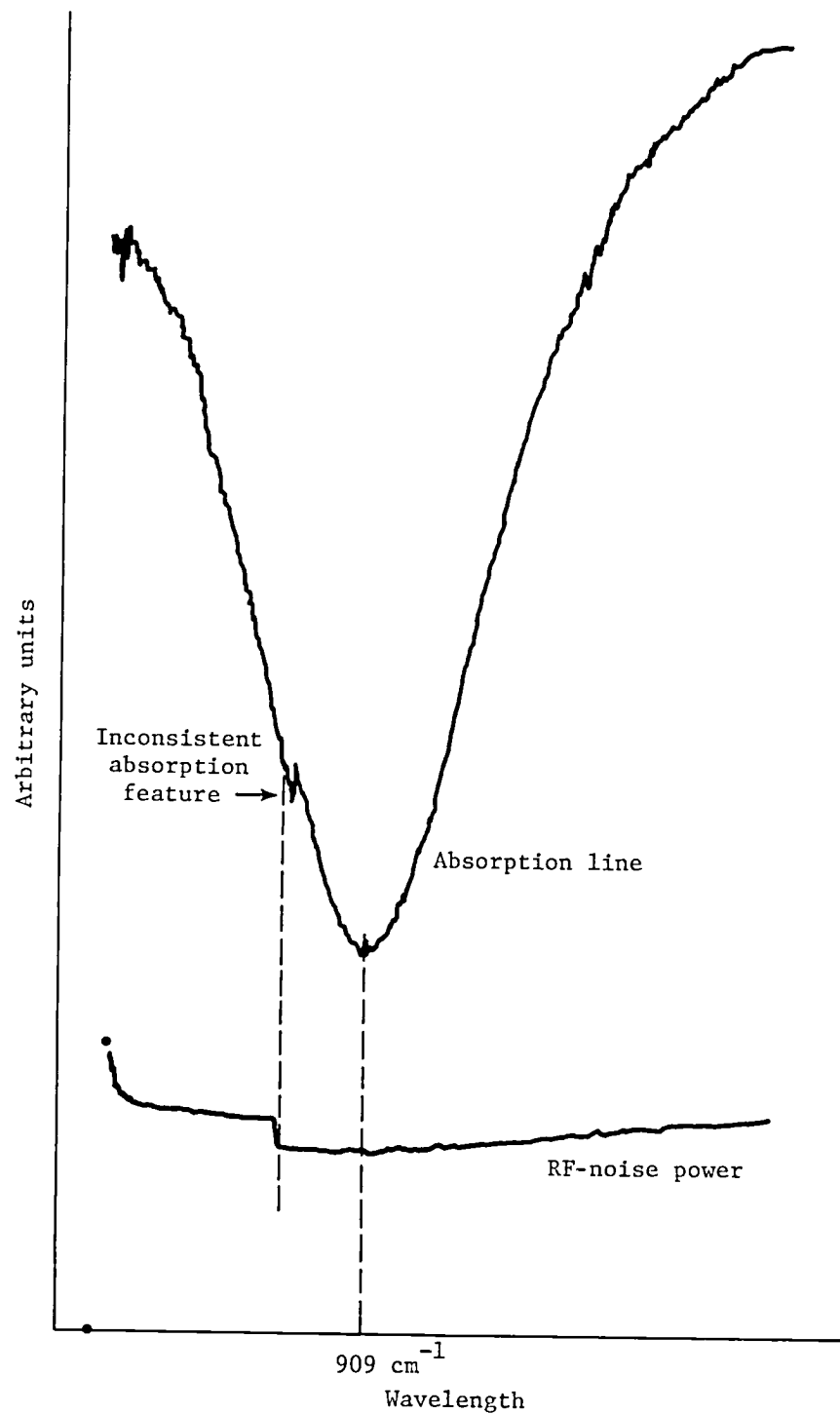


(a) First operating point.



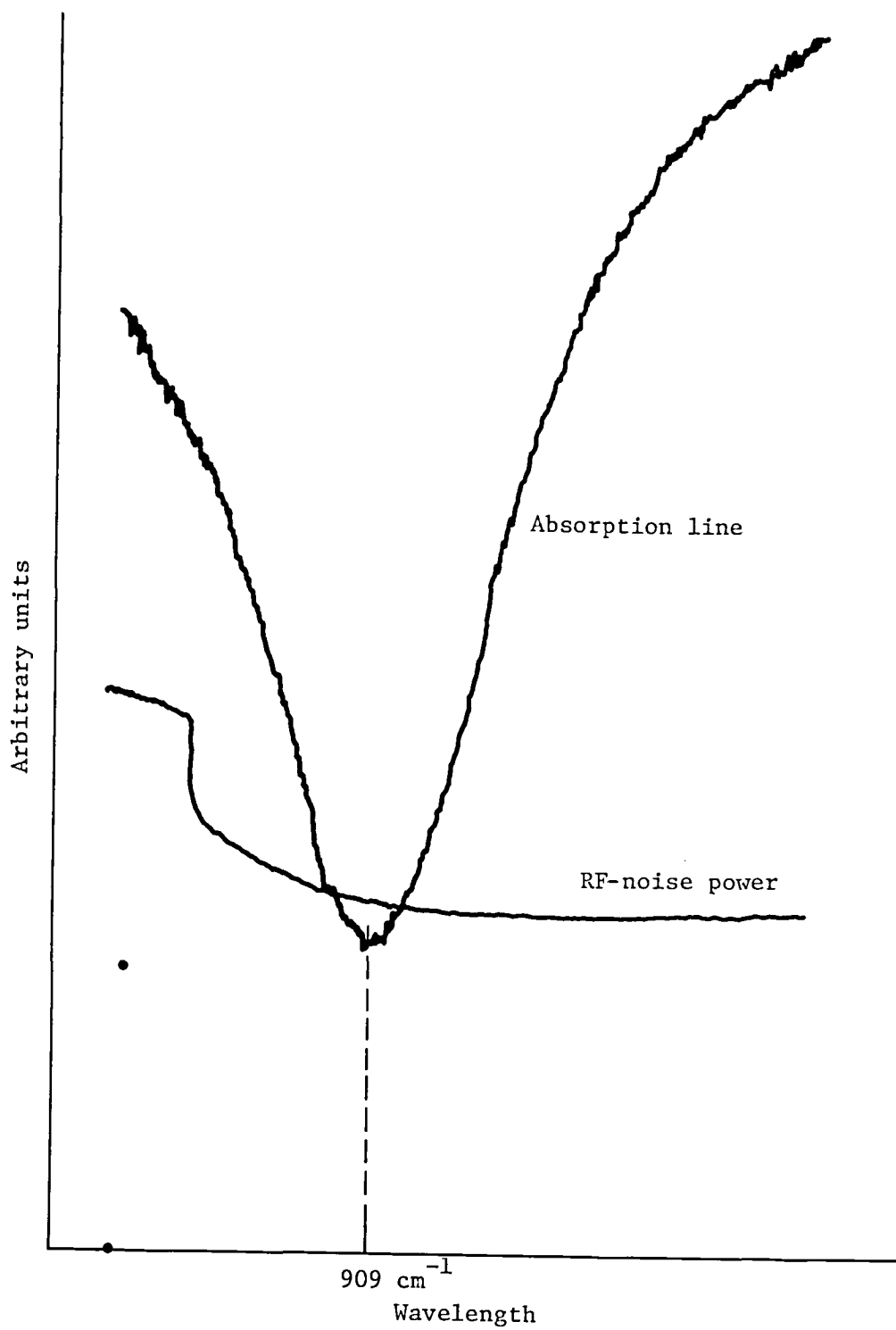
(b) Second operating point.

Figure 5.- Direct absorption of TDL by ammonia cell and excess noise in TDL's at two operating points.



(a) First operating point.

Figure 6.- Atmospheric water vapor absorption line and RF-noise power.



(b) Second operating point.

Figure 6.- Concluded.

1. Report No. NASA TP-1935		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle EXCESS NOISE IN TUNABLE DIODE LASERS				5. Report Date November 1981	
				6. Performing Organization Code 147-40-01-01	
7. Author(s) Carroll W. Rowland				8. Performing Organization Report No. L-14453	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665				10. Work Unit No.	
				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Paper	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>This paper describes the method and the apparatus for identifying excess-noise regions in tunable diode lasers. These diode lasers exhibit regions of excess noise as their wavelength is tuned. If a tunable diode laser is to be used as a local oscillator in a superheterodyne optical receiver, these excess-noise regions severely degrade the performance of the receiver. Measurement results for several tunable diode lasers are given. These results indicate that excess noise is not necessarily associated with a particular wavelength, and that it is possible to select temperature and injection current such that the most ideal performance is achieved.</p>					
17. Key Words (Suggested by Author(s)) Tunable diode laser Heterodyne Excess noise			18. Distribution Statement Unclassified - Unlimited Subject Category 36		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 14	22. Price A02		

For sale by the National Technical Information Service, Springfield, Virginia 22161

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